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Rossby waves in May and the Indian summer monsoon rainfall

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ABSTRACT

Large amplitude stationary Rossby wave trains with wavelength in the range 50° to 60° longitude have been identified in the upper troposphere during May, through the analysis of 200 hPa wind anomalies. The spatial phase of these waves has been shown to differ by about 20° of longitude between the dry and wet Indian monsoon years. It has been shown empirically that the Rossby waves are induced by the heat sources in the ITCZ. These heat sources appear in the Bay of Bengal and adjoining regions in May just prior to the onset of the Indian summer monsoon. The inter-annual spatial phase shift of the Rossby waves has been shown to be related to the shift in the deep convection in the zonal direction.

1. Introduction

The Indian summer monsoon rainfall (ISMR) from June to September has considerable inter-annual variability. The long-range forecasting of ISMR is not only a challenging scientific problem but also of great practical value for policy makers. Thapliyal (1997) has provided a review of the long-range forecasting techniques used by the India Meteorological Department (IMD) for predicting ISMR. The parameters used by IMD for the long-range forecast of ISMR are quantities such as Eurasian snow cover in winter, Southern Oscillation Index (SOI), surface temperature in India during March to May, the location of the 500 hPa ridge at 75°E in April and SST in the equatorial east Pacific ocean. Thapliyal (1997) has shown that the correlation coefficient between the ISMR and the independent parameters used for prediction changes with time. For example, the correlation coefficient between ISMR and the 500 hPa ridge (at 75°E in April) was very high in 1970s but declined rapidly by 1990. On the other hand, the correlation coefficient between ISMR and SOI has varied between 0.2 and 0.6 between 1970 and 1990. The correlation coefficient between ISMR and Himalayan snow cover has changed sign during the period 1970 to 1990.

The meridional wind in the upper troposphere in May is strongly correlated with ISMR but is not one of the sixteen parameters used by IMD for long-range forecasting. Joseph (1978) has shown that in years with deficiency in ISMR, the meridional winds in the upper troposphere were strong southerlies over India in May. Joseph et al. (1981) defined a meridional wind index (MWI) by averaging the meridional wind at 200 hPa over Chennai (Madras), Mumbai (Bombay), Nagpur, Delhi and Srinagar for the month of May. They showed that the linear correlation coefficient between ISMR and MWI during the period 1964 to 1978 was -0.83. They also found that correlation coefficient was equally high if instead of 200 hPa, data of 300 or 150 hPa in May were used. The correlation coefficient between ISMR and the 200 hPa meridional

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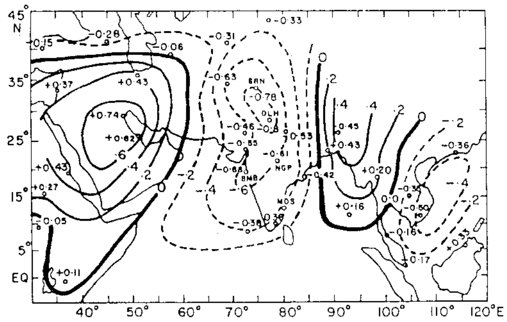

Fig. 1. Correlation between Indian summer monsoon rainfall (ISMR) and the monthly mean 200 hPa meridional wind of May (station data) for the period 1964 to 1978 (figure from Joseph et al., 1981).

winds in April or June was, however, poor. Using a longer time series, Parthasarathy et al. (1991) found that the correlation coefficient between ISMR and MWI of May 200 hPa was -0.72 during the period 1964–88 and the correlation was significant at the 99.9% level.

Joseph et al. (1981) had also examined the spatial structure of the correlation coefficient between ISMR and the May 200 hPa meridional wind for individual radio-wind stations in and around India. This is shown in Fig. 1 (from Joseph et al., 1981). Iso-lines of correlation coefficient are shown in the figure and the values for individual stations have also been indicated. Negative values of the correlation coefficient imply that southerly meridional wind anomalies occur in association with deficient ISMR (dry year). The correlation coefficient is negative over most of India and the maximum negative values occur over central and north-west India. An area of equally strong positive correlation is seen around Kuwait. There is another area with positive correlation coefficient over Myanmar (Burma) and an area with negative correlation coefficient further east. The cellular structure shown by the correlation coefficient indicates the existence of a stationary wave train with a wavenumber around 7 in the upper troposphere in May, with a wave-trough over the Arabian Sea during years of deficient ISMR. The aim of the present paper is to examine the nature of this wave in greater detail. It is shown in this study that this wave is part of a stationary Rossby Wave train. The Rossby wave pattern is induced in the sub-tropical westerlies by the convective heat sources associated with ITCZ as it moves from the southern hemisphere to the Bay of Bengal and the adjoining areas in May.

2. Data used

We have used the long homogeneous ISMR series derived by Parthasharathy et al. (1994). It

Table 1. *Indian summer monsoon rainfall (ISMR) data of 1961–1990 and their % departure from mean of 1871 to 1990*

Year	ISMR (mm)	% departure	Year	ISMR (mm)	% departure
1961	1020.3	19.7 wet	1976	856.8	0.5
1962	809.8	5.0	1977	883.2	3.6
1963	857.9	0.6	1978	909.3	6.7
1964	922.6	8.2	1979	707.8	−17.0 dry
1965	709.4	−16.8 dry	1980	882.8	3.6
1966	739.9	−13.2	1981	852.2	0.0
1967	860.1	0.9	1982	735.4	−13.7 dry
1968	754.6	−11.5	1983	955.7	12.1 wet
1969	831.0	−2.5	1984	836.7	−1.8
1970	939.8	10.3 wet	1985	759.8	−10.9
1971	886.8	4.0	1986	743.0	−12.8
1972	652.9	−23.4 dry	1987	697.3	−18.2 dry
1973	913.4	7.2	1988	961.5	12.8 wet
1974	748.1	−12.2	1989	866.7	1.7
1975	962.9	13.0 wet	1990	908.7	6.6

Data from Parthasarathy et al., 1994. Dry and wet years chosen for the study are marked.

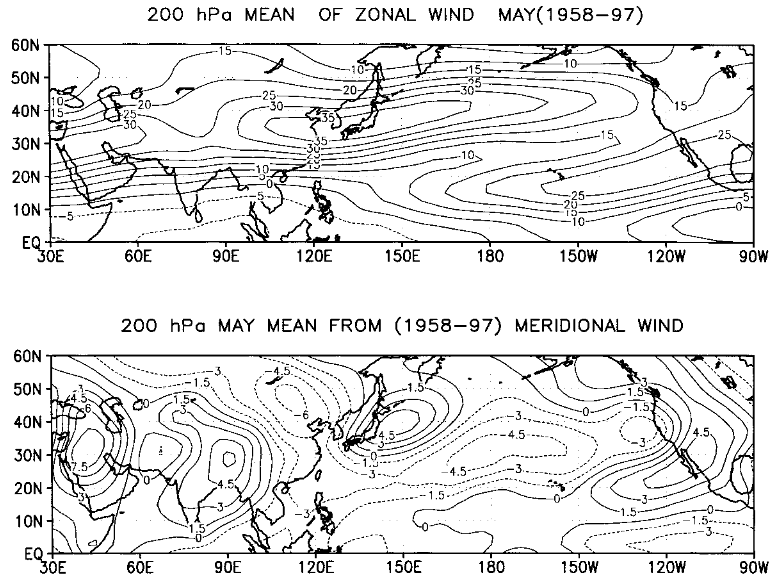

Fig. 2. (a) 200 hPa mean zonal wind (m/s) of May during the period 1958 to 1997. (b) 200 hPa mean meridional wind (m/s) of May during the period 1958 to 1997.

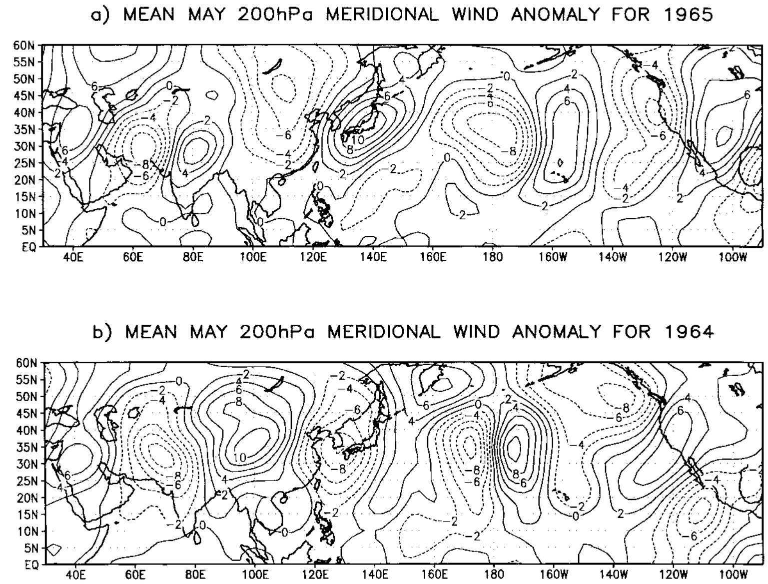

Fig. 3. (a) 200 hPa meridional wind anomaly (m/s) of May 1965, a year of below-normal monsoon rainfall. (b) 200 hPa meridional wind anomaly (m/s) of May 1964, a year of above normal monsoon rainfall. (Long period average given in Fig. 2 used to calculate anomaly.).

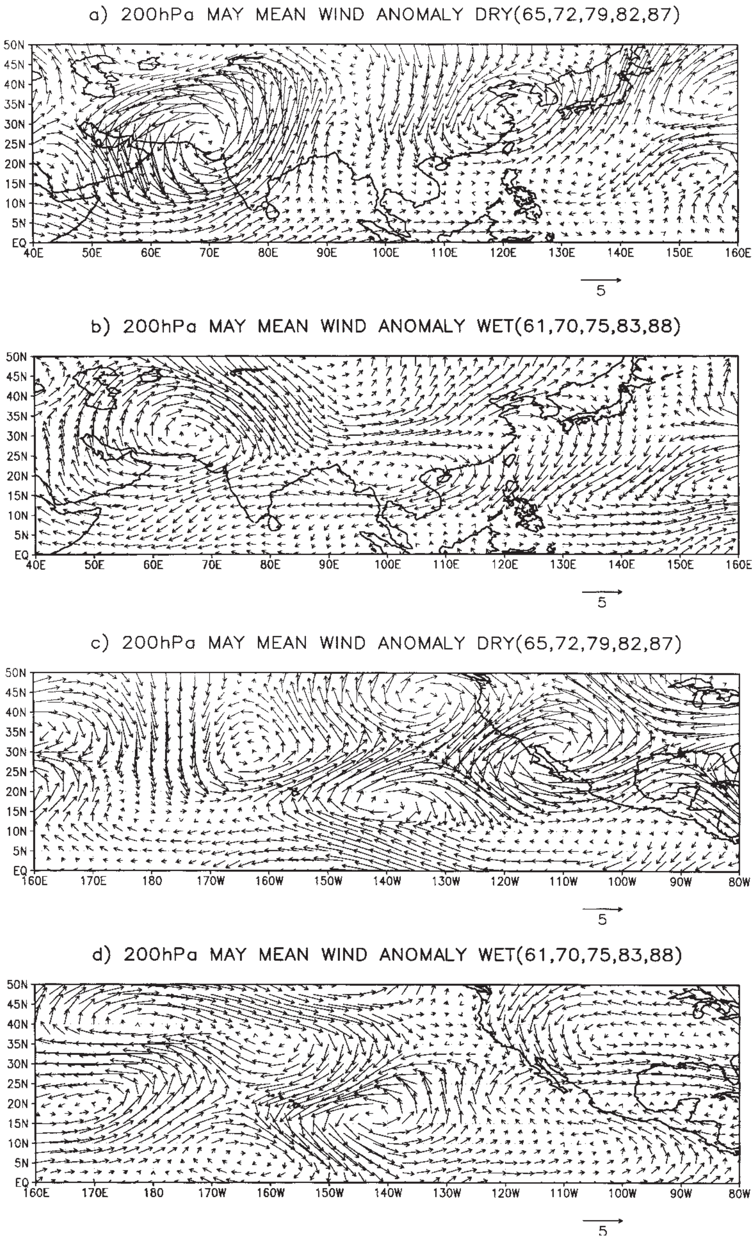

Fig. 4. (a), (c), (e): May 200 hPa wind anomaly (m/s) of composite dry years 1965, 1972, 1979, 1982 and 1987. (b), (d), (f): May 200 hPa wind anomaly (m/s) of composite wet years 1961, 1970, 1975, 1983 and 1988.

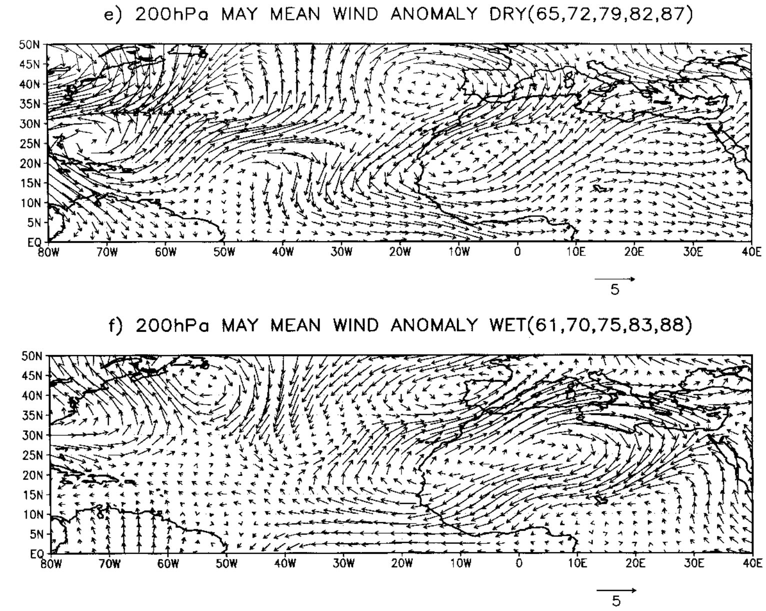

Fig. 4. (Continued)

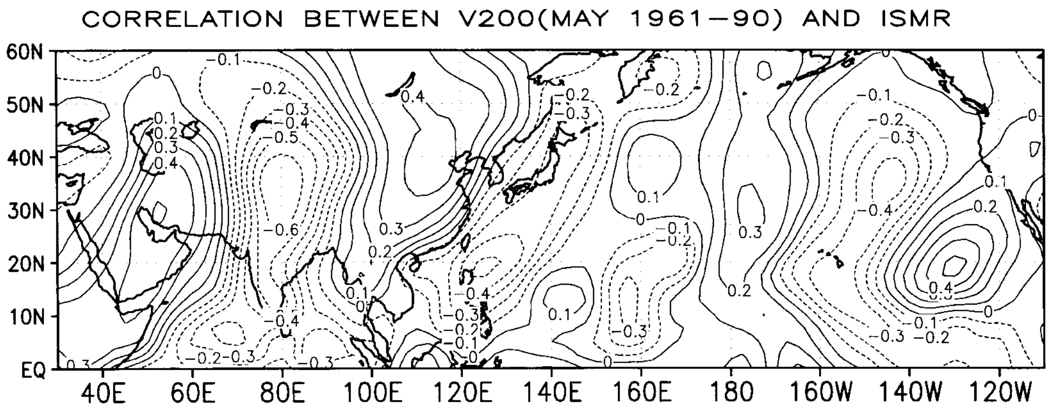

Fig. 5. Correlation coefficient between May 200 hPa meridional winds at grid points and ISMR during 1961 to 1990. Isolines at intervals of 0.1. Isolines with absolute value above 0.4 significant at 95% level.

is an area weighted average rainfall (1 June to 30 September) from 306 rain gauge stations well distributed over India. The long term mean ISMR for 1871 to 1990 is 852.4 mm and the standard deviation is 84.69 mm (9.9% of the mean). The dry years are years of large rainfall deficiency (more than one standard deviation) while wet years are with large rainfall excess (also more than one standard deviation). ISMR values and percentage excess or deficiency (departure from long term mean) for each year of the period 1961 to 1990 are shown in Table 1. In this paper, composites for dry and wet monsoon years have been made using the driest five years and the wettest five years during 1961 to 1990. These years are marked in Table 1.

The 200 hPa zonal and meridional wind components for May for the years 1958 to 1997 were

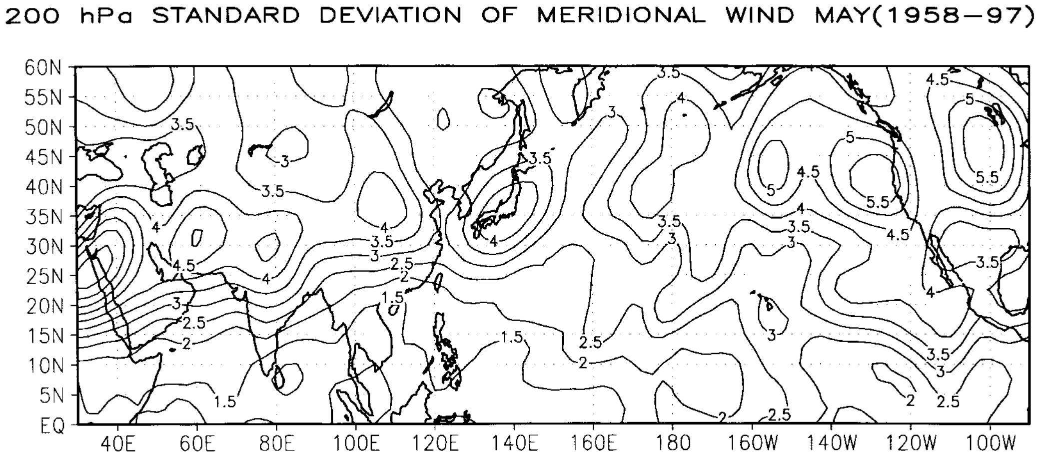

Fig. 6. Standard deviation (m/s) of May 200 hPa meridional wind for period 1958 to 1997.

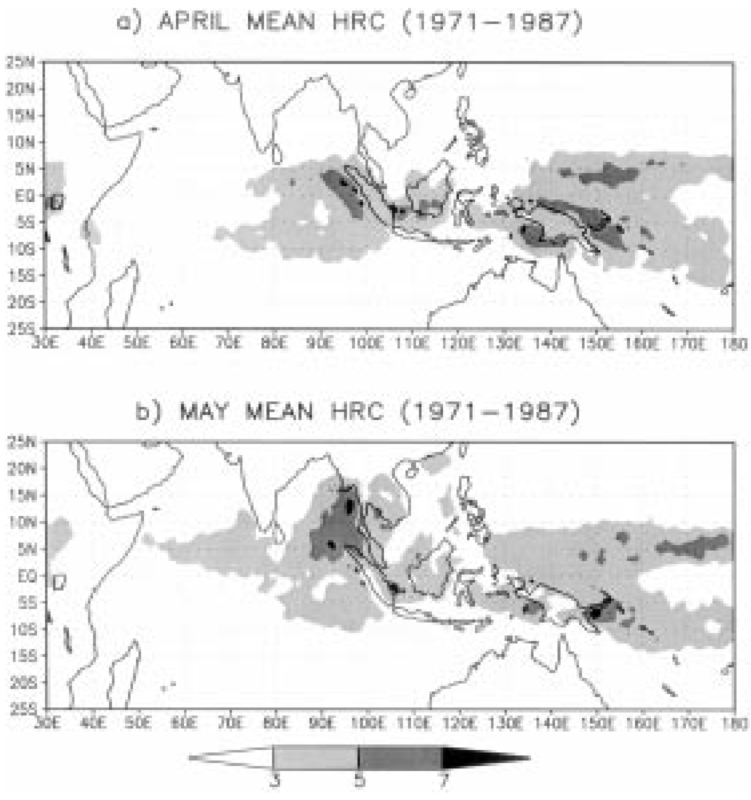

Fig. 7. (a) April mean HRC (days per month) during 1971 to 1987. (b) May mean HRC (days per month) during 1971 to 1987.

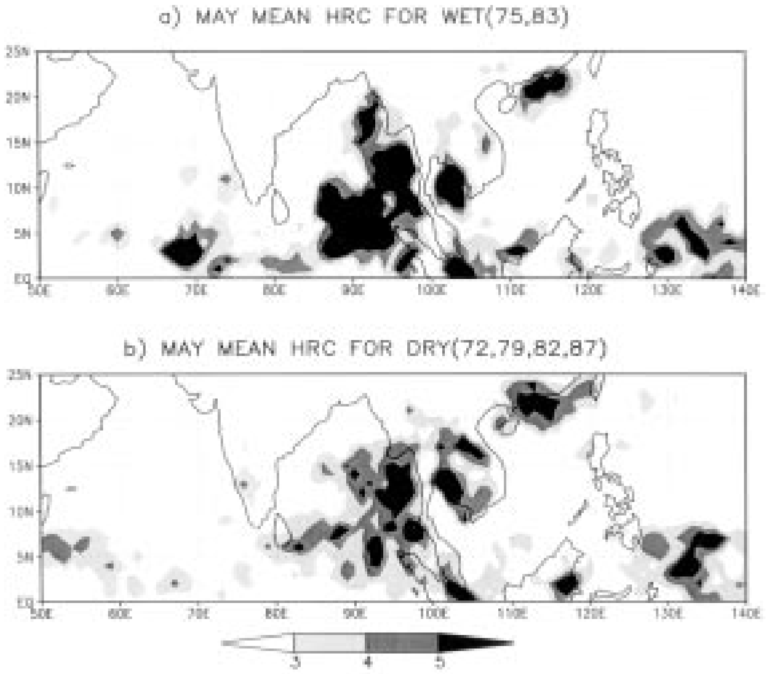

Fig. 8. (a) May HRC (days per month) wet composite (years 1975 and 1983). (b) May HRC (days per month) dry composite (years 1972, 1979, 1982 and 1987).

obtained from the NCEP Reanalyses (Kalnay et al., 1996). The monthly mean winds are on a $2.5^\circ \times 2.5^\circ$grid. The highly reflective clouds (HRC) data derived by Garcia (1985) has been used in this study to identify regions with deep convective clouds and heating. The spatial resolution of this data set is $1^\circ \times 1^\circ$ and extends from 25°N to 25°S and from 0°E to 359°E. The HRC monthly data set is available from January 1971 to December 1987. The total amount of missing data is only about 5% (Waliser et al., 1993).

3. Rossby waves during May

Long-term mean (1958–1997) zonal and meridional winds at the 200 hPa level are given in Fig. 2. The Asian Jet Stream has maximum zonal wind speeds in excess of 35 m/s and its axis extends eastwards across the Pacific (Fig. 2a). Between the African and Asian jet maxima, there is a region of weak winds north of India. In the stream line charts (not shown) this is a trough zone (partly shown by the strong southerly meridional winds in Fig. 2b). The base of the westerlies (zero isotach of zonal wind) passes through the north Bay of Bengal. Meridional wind anomalies (from the long term mean of 40 years) for May 1965 (departure of ISMR − 16.8%) and May 1964 (departure of ISMR + 8.2%), two adjacent years of contrasting ISMR have been shown in Fig. 3. The train of large amplitude waves of wavelenght 50°–60° longitude (zonal wave number 6–7) are prominent in both years, but there is a spatial phase difference of about 20° longitude between the weak (Fig. 3a) and strong (Fig. 3b) monsoon years. The waves follow the Asian jet stream and then move southeastwards to the USA, maintaining approximately the same phase difference all along. In the deficient monsoon year, the Indian region had anomalous southerlies while in the excess monsoon year the Indian region had anomalous northerlies. This is due of the fact that the Rossby wave of May has a different spatial phase during deficient and excess monsoon years. Note that similar differences in meridional wind are also observed around the

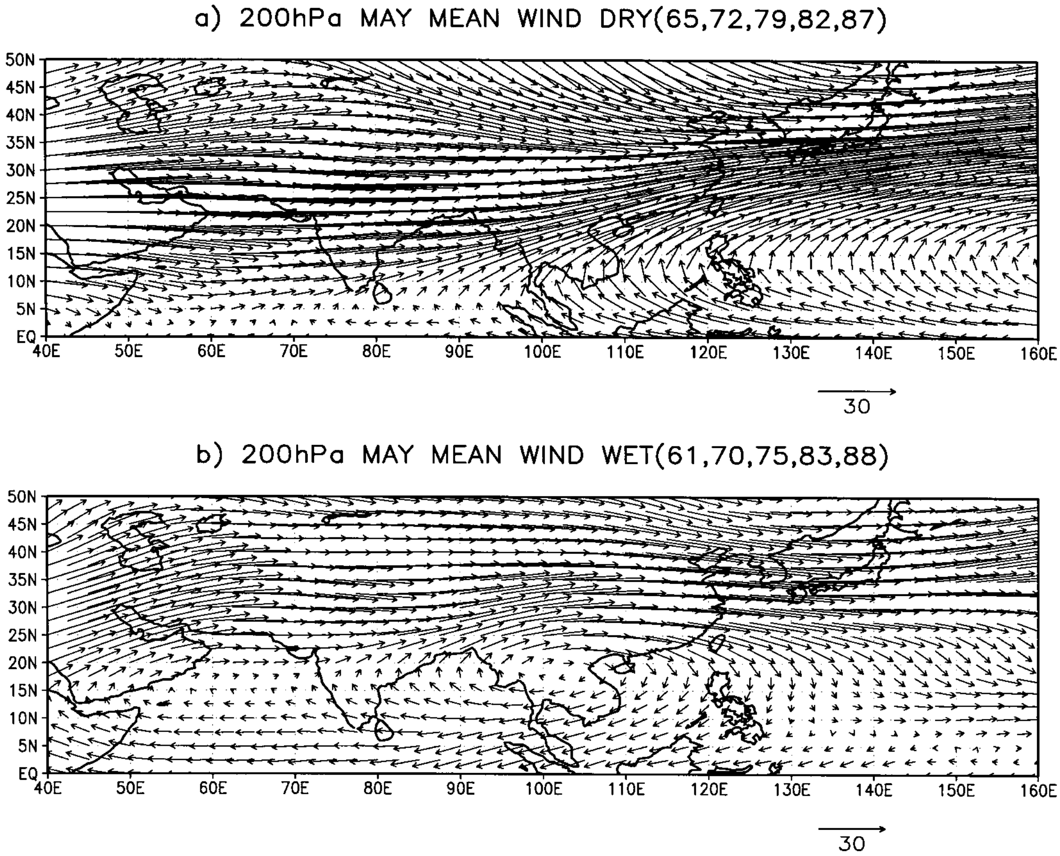

Fig. 9. (a) May 200 hPa total wind field (m/s) of dry composite (years 1965, 1972, 1979, 1982 and 1987). (b) May 200 hPa total wind field (m/s) of wet composite (years 1961, 1970, 1975, 1983 and 1988).

Japanese islands and further east. The composite anomaly vectors of May wind (total wind) for 5 dry and 5 wet years around the globe is shown in Fig. 4 for three longitudinal sectors covering the whole globe between equator and 50°N latitude. The individual years of each composite have shown remarkable similarity in the phase of the wave. Over northwest India and regions around a cyclonic vortex is seen in dry years and an anticyclonic vortex in wet years (Figs. 4a, b). A similar feature associated with the following wave is seen around Japan. Over the central and east Pacific ocean the wave path moves to more southerly latitudes in the wet composite (Figs. 4c, d) and moves to more northerly latitudes over the Atlantic ocean (Figs. 4e, f).

Fig. 5 gives the spatial variation of the correlation coefficient between the 200 hPa meridional wind of May at each grid point (2.5° × 2.5°) and the ISMR of the same year for the 30 year period 1961–1990. The pattern of positive and negative correlations is similar to the wave pattern in Fig. 3 showing clearly a Rossby wave that is associated with the strength of the following ISMR. The ±0.4 isopleth of correlation is significant at 95% level for each grid point. The spatial coherence in meridional wind between adjacent grids can however lower the significance level (Livezey and Chan, 1983). We generated 1000 new synthetic 30 year ISMR data by random permutation of the original observed ISMR. The correlation between the 250 mb meridional wind and the synthetic ISMR data was calculated. We found that the absolute value of correlation coefficient in the

Indian region (20°N–40°N 70°E–80°E) exceeded 0.4 in 31 out of the 1000 simulations. Hence our conclusion that the correlation coefficient above 0.4 (absolute value) represents 95% significant level is not invalidated.

The standard deviation of the 200 hPa monthly mean meridional wind of May during the 40 year period 1958–1997 is shown in Fig. 6. This shows clearly that there is a phase shift of half a wavelength in the Rossby waves between weak and strong monsoon years. There are small areas of large standard deviation all along the path of the Rossby wave train. They are spaced 25–30° longitude apart (i.e., about half the wavelength of the Rossby wave).

4. Rossby wave source

The equatorial convective cloudiness maximum (ECCM) commonly known as the ITCZ (intertropical convergence zone) has a prominent annual cycle. The movement of the ECCM between April and May is shown in Fig. 7. The 17-year (1971–1987) mean monthly HRC has been used to document the seasonal northward shift in ECCM. In April ECCM is at the equator. In May (Fig. 7b), the region of active convection is well north of the equator over the Bay of Bengal and the surrounding land and sea. Over the rest of the tropics ECCM continues in its April position (number of days during which deep convection occurs exceeds three per month are marked in the figure). The deep convective heat source over the Bay of Bengal and adjacent regions and the upper tropospheric divergence associated with it can serve as a Rossby wave source as shown by Sardeshmukh and Hoskins (1988). This convective heat source slowly builds up from about 10 May and reaches maximum in area and intensity by the end of May, the normal date of onset of monsoon over Kerala (Pearce and Mohanty, 1984; Joseph et al., 1994). This Rossby wave source in May shows large shift in the east-west direction between weak and strong monsoon years. There were 4 dry and 2 wet years during the period for which HRC data is available (1971 to 1987). The area occupied by deep convective clouds (3 or more days per month) in May during these dry and wet years is shown in Fig. 8. We find a westward expansion, by about 20° longitude, in the area occupied deep convective clouds during wet monsoon years. In wet years, the deep convective clouds occur between longitudes 70°E and 100°E (Fig. 8b), whereas in dry years they occur between 90°E and 120°E (Fig. 8a).

Deep convective heating warms the upper troposphere creating an upper troposphere anticyclone. Fig. 9 shows the composite of May monthly mean wind at 200 hPa. The composite is for the 5 dry years shown in Fig. 4. The divergent anticyclonic area is centred over the Philippines islands between longitudes 100°E and 150°E and latitudes 5°N and 20°N. Fig. 9b shows the composite of May monthly mean wind at 200 hPa for the 5 wet monsoon years. The divergent anticyclonic area at 200 hPa associated with the convective heating (which is a Rossby wave source) may be seen centred over Myanmar and extending between longitudes 80°E and 130°E and between latitudes 10°N and 25°N.

That the Rossby wave source has an east–west shift between dry and wet years is better seen from the composites for the May 200 hPa velocity potential field in Fig. 10. The composites are for the same 10 years as in Fig. 4 (5 for dry and 5 for wet). In the wet composite, the core of the divergent area has shifted westwards compared to the dry case.

5. Discussion

A prominent wave is seen in the upper tropospheric sub-tropical and mid-latitude westerlies in May in all years. It has wavelength of 50 to 60° longitude and has a large amplitude. The spatial phase of the wave is found to depend on the longitudinal position of the convective heat source associated with the ITCZ. In weak monsoon years, when the heat source occupies a more eastward location, there is a corresponding eastward shift in the wave. Such an eastward shift of many large-scale features associated with a weak monsoon year has been documented by Kanamitsu and Krishnamurti (1978). This wave shows the major characteristics of stationary barotropic Rossby wave obtained from observations, theory and modelling as summarized by Ambrizzi and Hoskins (1997). The wave follows the westerly Asian jet waveguide from Asia well into the Pacific Ocean. The barotropic structure of the wave was

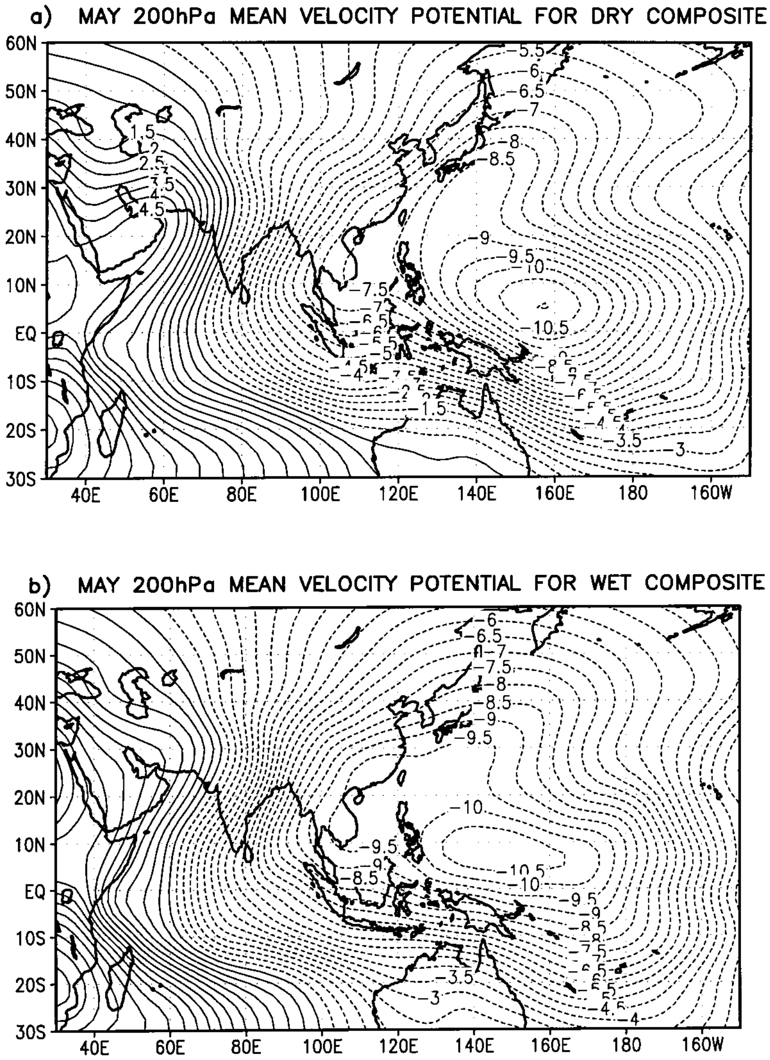

Fig. 10. (a) Velocity potential for May 200 hPa for dry composite (years 1965, 1972, 1979, 1982 and 1987) (velocity potential in units of $10^6\ m^2\ s^{-1}$). (b) Velocity potential for May 200 hPa for wet composite (years 1961, 1970, 1975, 1983 and 1988) (velocity potential in units of $10^6\ m^2\ s^{-1}$).

tested using data of 1982 May. For this the meridional wind is averaged over the latitudinal band 20°N to 50°N for May 1982. The meridional wind anomaly was calculated as deviations from the mean for 1982 to 1994 for four levels 200, 300, 500 and 700 hPa. The wave has very little phase shift with height. Wave amplitudes are maximum at 300 and 200 hPa levels and decreases at 500 and 700 hPa.

A question arises, as to whether there is Rossby wave activity in April. There is no wave activity seen in April for the dry composite of 5 years. What is seen is westerly anomalies from equator to 20°N and easterly anomalies in the region of the subtropical westerly jet stream, 25°N to 35°N (weaker subtropical jet stream). However, in the April wet composite, a Rossby wave train is seen as in the wet May composite, but much weaker.

This is consistent with the poor correlation between ISMR and MWI in April found by Joseph et al. (1981).

The stationary Rossby wave train generated by the convective heat source over south Asia in May, let us call it the Asia Pacific wave (APW), propagates with large amplitude across the Pacific to North America and beyond and its phase varies from year to year. It is likely that this wave, like the well-known PNA pattern, influences the weather and climate along its path. It is very likely to influence tropical cyclone tracks in the western part of the north-Pacific Ocean, the weather and climate of Japanese islands and possibly those of the western part of United States of America.

6. Acknowledgements

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